Coupled High-Resolution Modeling of the Earth System

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V. Balaji

Princeton University

NOAA/GFDL

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Outline

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1. NOAA-DOE mission goals

2. Why high resolution?
   - Regional scales are better represented
   - Fundamental new physics in atmosphere and ocean
   - Decadal predictability
   - Hurricanes and climate change

3. The CHiMES Project
   - NOAA models for these studies
   - Coupled model experiments and target resolutions
   - Schedule and requirements

4. References

NOAA-DOE mission goals

NOAA and DOE share goals in understanding and predicting climate change and its impact. This joint activity will

- support NOAA"s mission to understand and predict changes in the Earth's environment by
  - improving climate predictive capability from weeks to decades with an increased range of applicability for management and policy decisions
  - developing and contributing to routine state-of-the-science assessments for informed decision making
- support DOE's research and modeling efforts to
  - predict accurately any global and regional climate change induced by increasing atmospheric concentrations of aerosols and greenhouse gases
  - improve the scientific basis for assessing both the potential consequences of climatic changes, including the potential ecological, social, and economic implications of human-induced climatic changes caused by increases in greenhouse gases in the atmosphere and the benefits and costs of alternative response

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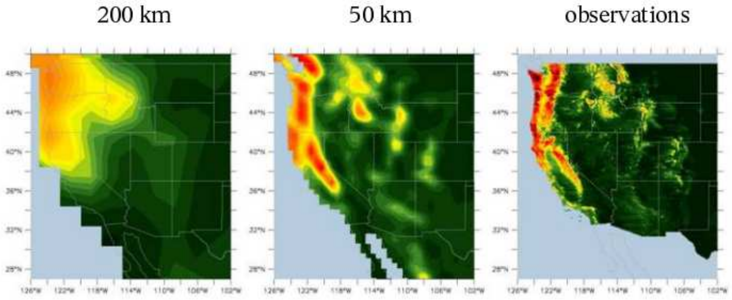
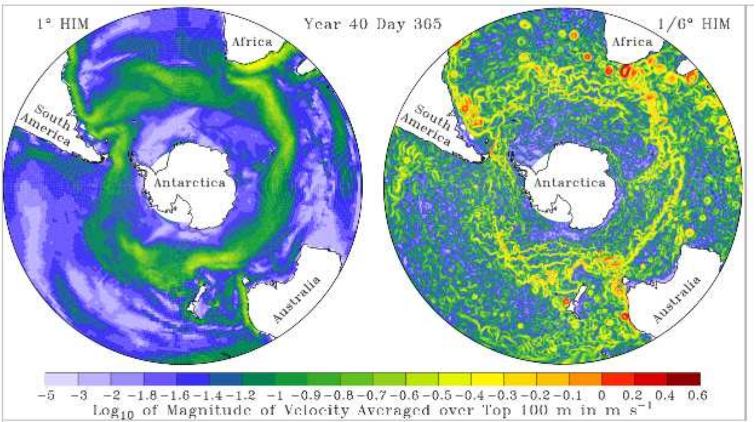
Regional scales are better represented



- There is a dramatic improvement in our ability to model regional scale climate response as we go to “high” (i.e beyond the IPCC AR4 norm) resolution.
- *Petascale computing* becomes a requirement the long control integrations needed for detection and attribution of climate change above the threshold of natural variability.

Ocean eddies

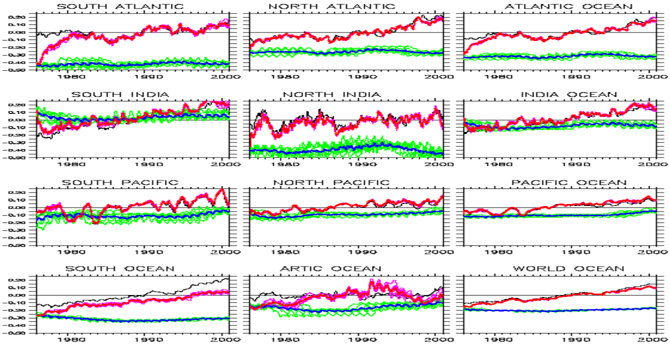


Shaded is the speed of the surface currents in the ocean model at two resolutions.

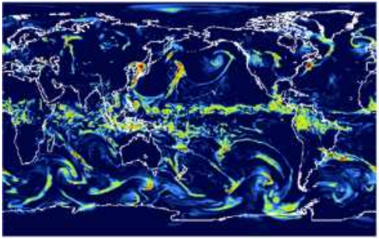
At 15 km resolution, turbulent eddies in the ocean are directly simulated, and show fundamentally different heat transport on climate scales.

Decadal predictability in the Atlantic

Just as ENSO in the Pacific may modulate climate on a timescale of a few years, the modes in the Atlantic may modulate climate on decadal timescales. This is currently being proposed as the basis for decadal climate prediction (Keenlyside *et al* 2009; Smith *et al* 2007).
Can models reproduce decadal predictability?

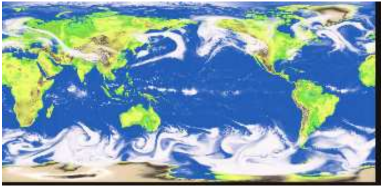


Tropical storm systems; mid-latitude fronts; clouds



25 km

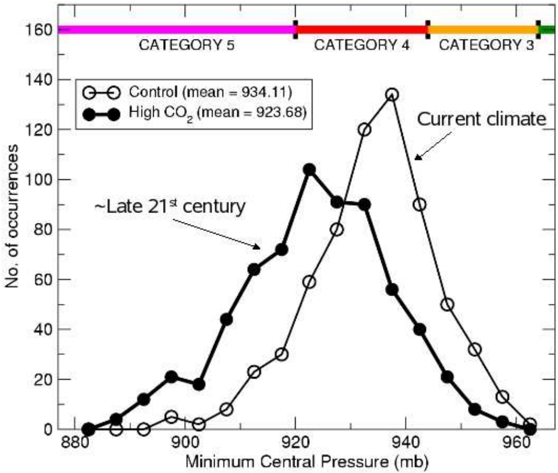
At 25 km resolution, we can study the statistics of tropical cyclones under climate change.



5 km

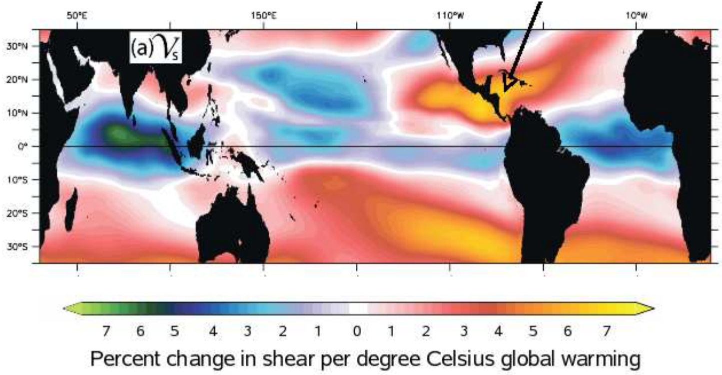
At 5 km resolution, we arrive at the long-awaited “global cloud-resolving model”, and the potential to dispense with paramaterizing deep convection in climate models.

Hurricane intensities are projected to increase. . .



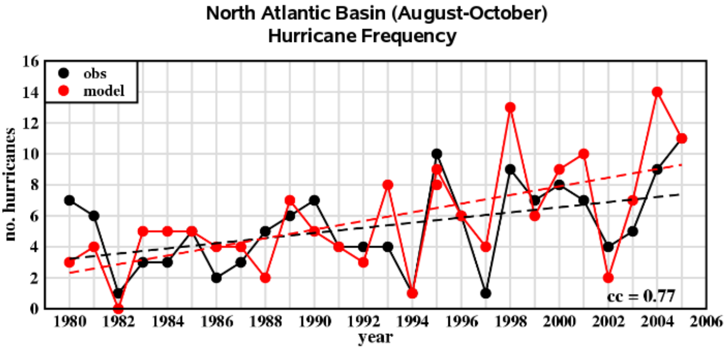
Hurricane models forced by CMIP data project increased intensities in a warmer world (Knutson and Tuleya 2004).

However, hurricane frequencies might decrease. . .



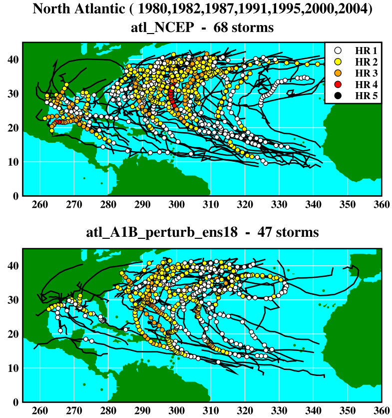
Vecchi and Soden (2007) show wind-shear increasing in a warming world, potentially leading to a decrease in Atlantic hurricane frequency (though not elsewhere. . .)

NOAA high-resolution models capture hurricane statistics



NOAA regional model ZETAC captures inter-annual variability in hurricane frequency when forced with historical data (Knutson et al 2007). This study is being repeated now for a warming world from IPCC AR4 data to confirm or refute Vecchi and Soden.

Vecchi and Soden results corroborated



Preliminary regional model results show reduced Atlantic hurricane frequency in the late 21st century. Forced regional model results need to be supported by global coupled models for a complete understanding of this key result. NOAA models are ready to make the leap given enough computing and analysis power.

Science in support of NOAA-DOE mission goals

- High-resolution models can be used to provide improved understanding of regional climate change.
- Understanding and analyzing the inherent predictability of models at high resolution will help design international modeling campaigns aimed at climate prediction.
- Understanding tropical storm statistics using high-resolution global models provides insight in planning for extreme events in a warming world.
- The science therefore fulfils the NOAA and DOE missions of providing a *predictive understanding* of climate change, and providing *credible and timely information for decision makers* in preparing for climate change.

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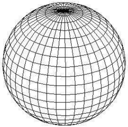
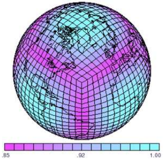
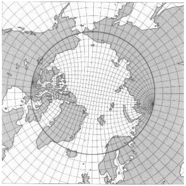
NOAA Models and the FMS Mosaic infrastructure







- The Finite-Volume conventional grid dycore (`FVLL`): Fourier filter at the pole limits scalability on distributed memory.
- The Finite-Volume Cubed-Sphere dycore (`FVCS`) eliminates the pole and vastly increases scalability on distributed memory.
- The ocean model in these experiments is `MOM4`, running on a tripolar grid: also has no pole problem. The newer `GOLD` model also is tripolar.
- Parallelism in all the models is provided by the FMS `Mosaic` infrastructure, which handles parallel I/O and communication (`MPI`, `shmem`, threads).

Coupled model experiments and target resolutions

Experiments are designed to understand model behaviour and climate predictability at high resolution, and to study year-over-year changes in hurricane frequency and intensity in a warming world.

- Control integrations of high-resolution versions of `CM2.1`, the NOAA/GFDL flagship model. `CM2.4` will double atmospheric resolution to 1° (C90) and quadruple the ocean resolution to 0.25° (MOM4p25). `CM2.5`: atmospheric resolution increased to 0.5° (C180).
- $2\times CO_2$ control of `CM2.4` and `CM2.5`.
- AMIP runs of `AM2` model configured with next-generation atmospheric dynamical core ("Finite-Volume Cubed-Sphere") at 0.5° and 0.25°.
- "Time-slice" experiments of the high-resolution AM2 models above forced with data from the $1\times CO_2$ and $2\times CO_2$ `CM2.4` runs.

Projected performance and throughput

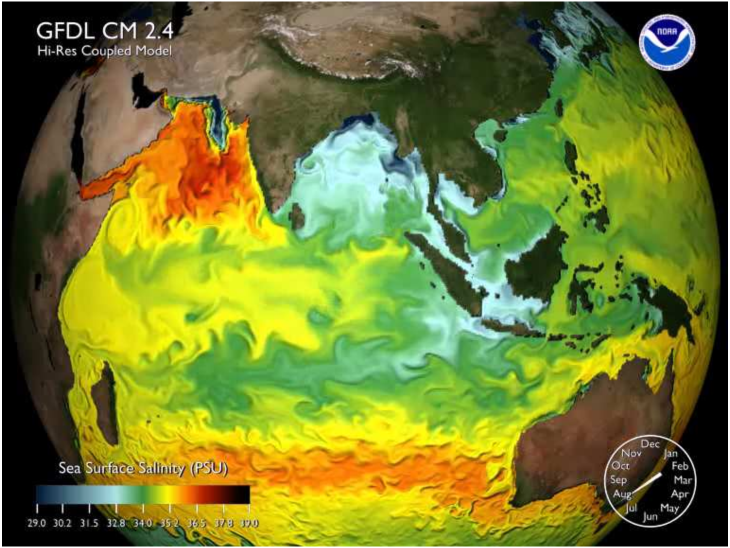
Model	PE Count	model y/d	CPU-h/m	Data out (GB/d)
CM2.4	2400??	3.5	345600	550
AM2C180	1536	4	360000??	350
AM2C360	3456??	2	720000??	700

- Throughput numbers assume dedicated CPUs: no queue wait time.
- `AM2C180` is expected to reach 50% scalability at 2560 cores; `AM2C360` at 10240 cores. Actual PE counts to be decided after further measurement.
- We plan to stream data back to GFDL for post-processing and analysis: minimum sustained bandwidth requirement of 150 Mbps not counting software stack (encryption, firewall, checksums, . . .).

Aggregate costs of proposed runs

- If these projections hold up, one run each of CM2.4, AM2C180, AM2C360 would require 2400 dedicated cores (1.44M CPU-hours/month).
- Rule of thumb for “scientifically useful” runs is a minimum of 3-4 model-years/day (100 y/month). Current projected throughput is marginal and assumes dedicated CPUs: no queue wait time.
- Aggregate data bandwidth of 1.6 TB/day may be an issue.

Preliminary results from CM2.4



FY2008 and beyond

- Decadal (and longer) predictability studies and hurricane statistics under climate change both require ensemble runs. We could easily use as much as is made available given other constraints such as data volume.
- Public dissemination of data from high-resolution models: this would be a valuable community resource in planning the next cycle of international modeling campaigns.
- And beyond. . .
  - Global non-hydrostatic FVCS (C2000) with full cloud physics enabled.
- More info: `http://www.gfdl.noaa.gov/~vb/chimes/`

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- Emanuel, K. A., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686–688.
- Griffies, S. *et al*, 2005: Formulation of an ocean model for global climate simulations. *Ocean Science*, **1**, 45–79.
- Keenlyside, N. S., *et al*, 2008: Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 84–88, doi:10.1038/nature06921.
- Knutson, T. R., *et al*, 2007: Simulation of the recent multidecadal increase of atlantic hurricane activity using an 18-km-grid regional model. *Bull. Amer. Met. Soc.*, **88**, 1549–1565.
- Knutson, T. R., *et al*, 2008: Simulated reduction in atlantic hurricane frequency under twenty-first-century warming conditions. *Nature Geoscience*, **1**, 359–364.
- Smith, D. M., *et al*, 2007: Improved surface temperature prediction for the coming decade from a global climate model. *Science*, **317**, 796–799.